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TRAVELING-WAVE TUBE MIXER PROGRAM

3rd INTERIM ENGINEER REPORT

SPERRY GYROSOPE Co

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THIRD INTERIM ENGINEERING REPORT
COVERING PERIOD 1 NOVEMBER 1961 THROUGH 31 JANUARY 1962

AERONAUTICAL SYSTEMS DIVISION
WRIGHT AIR DEVELOPMENT DIVISION
WRIGHT-PATTERSON AIR FORCE BASE
DAYTON, OHIO

ELECTRONIC TUBE DIVISION
SPERRY GYROSCOPE COMPANY
DIVISION OF SPERRY RAND CORPORATION
GREAT NECK NEW YORK

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Contract No. AF 33(616)-8074

February 1962

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ABSTRACT

A low-noise electron gun has been tested and evaluated. The coupler design has been reevaluated, and a new magnet chosen for the experimental mixer tube. The status of construction of the tube is reported. A possible design of a full frequency mixing device is mentioned.

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SECTION I
INTRODUCTION

This report covers the period 1 November 1961 through 31 January 1962, and has been prepared under Contract No. AF 33(616)-8074 for the Aeronautical Systems Division by the Electronic Tube Division, Sperry Gyroscope Company Division of Sperry Rand Corporation, Great Neck, New York.

The first interim engineering report of this series posed the problem of building a unienvelope, single electron beam device. The purpose of this device is to fulfill the functions of a low-noise amplifier, local oscillator, frequency mixer, and i-f amplifier for incoming signals in the four- to six-millimeter wave region, and proposed four possible solutions to the problem; two space charge wave devices, one cyclotron wave device, and a two-helix traveling-wave tube.

The second interim engineering report contained a description of the design of the two helix sections of a scaled two-helix traveling-wave tube mixer, down converting a signal at X-band to one at L-band. The anticipated mixing action was calculated and the problems associated

with the external helix coupler design were considered. In the same report, a theoretical analysis eliminated the space charge wave devices as possible contenders.

Included in the present report is an evaluation of the possibilities of using the cyclotron wave device as a mixer. Progress to date in the construction of the two-helix traveling-wave tube mixer is discussed in detail. The low-noise electron gun to be used with the experimental traveling-wave tube mixer is also discussed. The external coupling helix design is reevaluated to insure optimum coupling at all frequencies. A preliminary investigation of the full-frequency mixing device has begun, and will be evaluated as the program continues.

As more and more is learned about broadband cyclotron wave devices, it becomes apparent that a great deal of additional work must be performed before even the most elementary device becomes an operating reality. Since the building of a complex multiple function device envisioned in this program is predicated on the proposition that the more elementary devices are accomplished facts, it would seem highly doubtful at this time that a cyclotron wave device could be conceived, designed, and built within the time scale of the current program.

The present day limitation on cyclotron wave parametric wave amplifiers is related to the small variations in axial velocity, due to such things as thermal effects, space charge effects, and lens effects. An analysis of these phenomena appears in Appendix A. It is evident from this analysis that these effects are

minimized for the special case of infinite phase velocity $\omega = \omega_c$ (Omega equals Omega sub c). Adler[1] and Ashkin[2] have built successful devices by working entirely with infinite phase velocities. More recently Hrbek[3] was able to build a successful non-degenerate device by employing the signal frequency as an infinite phase velocity signal, and permitting the idler frequency to suffer the various velocity degradations. Unfortunately, this type of manipulation would not be possible in a mixer tube, since the idler frequency becomes the i-f, and is of as much importance as the signal frequency.

There are several programs under way, at various laboratories, that are attempting to circumvent the velocity differential problems. If any of these programs are successful, it will then be apropos to reconsider the cyclotron wave device as a possible mixer. The expectation is that results from these programs will be available only toward the end of the present mixer program. Therefore, all effort on the present mixer program should be devoted to the traveling-wave tube approach as representative of the most promising attack of the problem. This approach will then be pursued for the remainder of the program.

SECTION II
DESIGN OF THE TWO-HELIX MIXER

2-1. LOW-NOISE ELECTRON GUN

The low-noise electron gun to be used in the traveling-wave tube mixer is a solid-cathode scaling[4] of a hollow cathode design first proposed by Currie[5] and Forster[6]. The solid-cathode design of Caulton and St. John[4] was designed for use at S-band, further scaling was therefore required for use in the X-band mixer tube. The low-noise electron gun, to be used in the traveling-wave tube mixer, has a solid button oxide-coated cathode. The electron gun consists of a cathode, beam-forming electrode, and four anodes. A 3/4-cutaway view of the low-noise electron gun is shown in figure 1.

The electron gun was designed to operate at a beam voltage of 900 volts and a beam current of 200 microamps. The electron gun perveance at standard operation was 0.0074 microperveance. The electron gun was constructed and assembled in a glass envelope. This envelope was then glassed to a collector. A drift space of 0.015 inch separated the electron gun drift tube and the

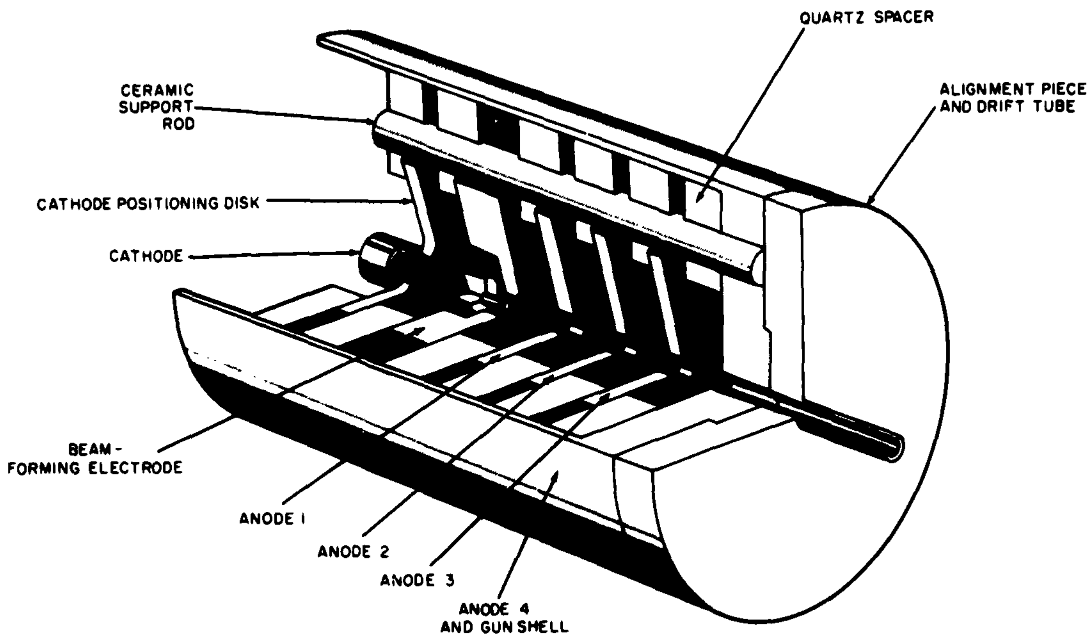

FIGURE I. LOW-NOISE ELECTRON GUN, 3/4-CUTAWAY VIEW

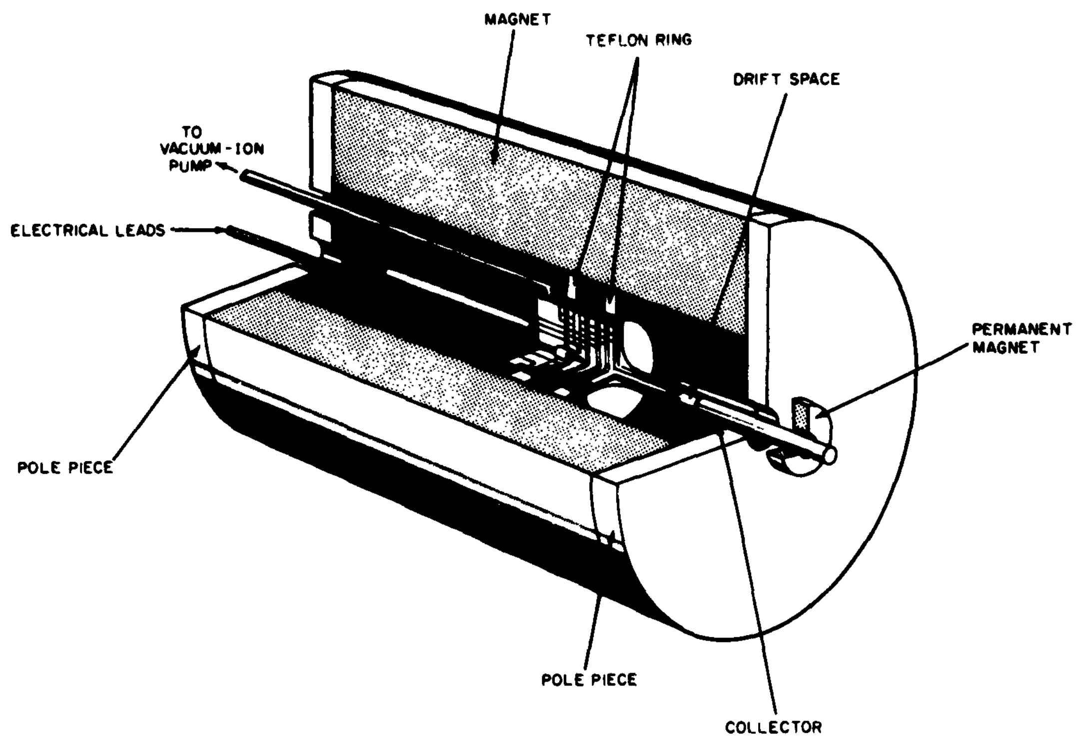

FIGURE 2. LOW-NOISE ELECTRON GUN TEST SET-UP, 3/4-CUTAWAY VIEW

collector. Tests were then made on the experimental diode. The test set-up is shown in figure 2.

The voltages at the cathode, beam-forming electrode, all anodes, and heater were monitored. Beam and magnet currents were also monitored. The tests began on 30 October 1961, and were concluded on 20 November 1961 after approximately 500 hours of continuous operation. The initial perveance curve is shown in figure 3. The desired heater voltage was seen to be 5.0 volts. For this initial operation, the beam-forming electrode was connected to the cathode and all anodes were connected to ground. When the gun was arranged for different voltages on all electrodes, as in actual tube operation, the heater voltage was raised to 5.5 volts. At this voltage (5.5 volts), the best gun performance and longest cathode life were attained. The gun was also overdriven so as to increase the current density from 63.3 ma/cm^2 to 200 ma/cm^2. The gun functioned satisfactorily at this increased current with only a slight drop in percent of beam transmission. The overdriven case perveance curve is shown in figure 4. Table 1 shows the results of the initial, optimum, and overdriven cases. The magnetic field found to be best suited for use with the tube was approximately 450 gauss. This was achieved by using aluminum wafer magnets rated at 110 gauss/amp.

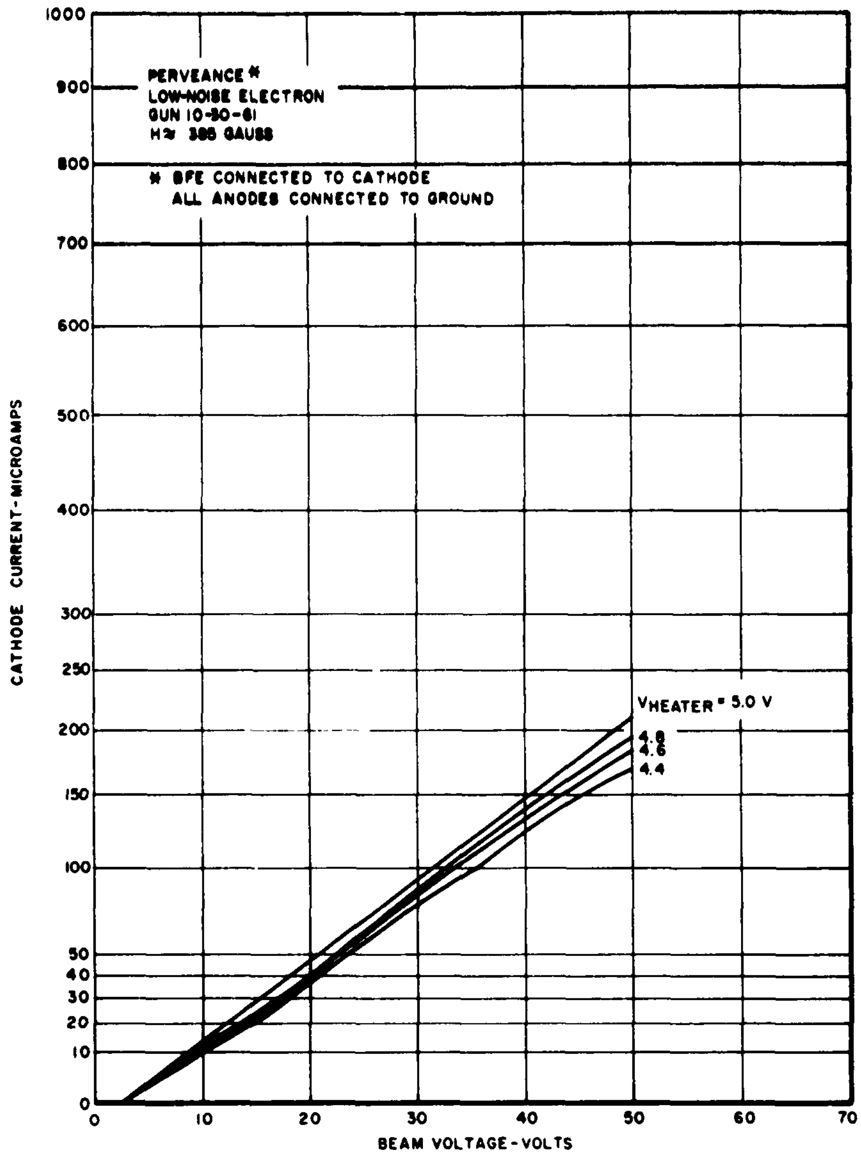

FIGURE 3. INITIAL PERVEANCE CURVE

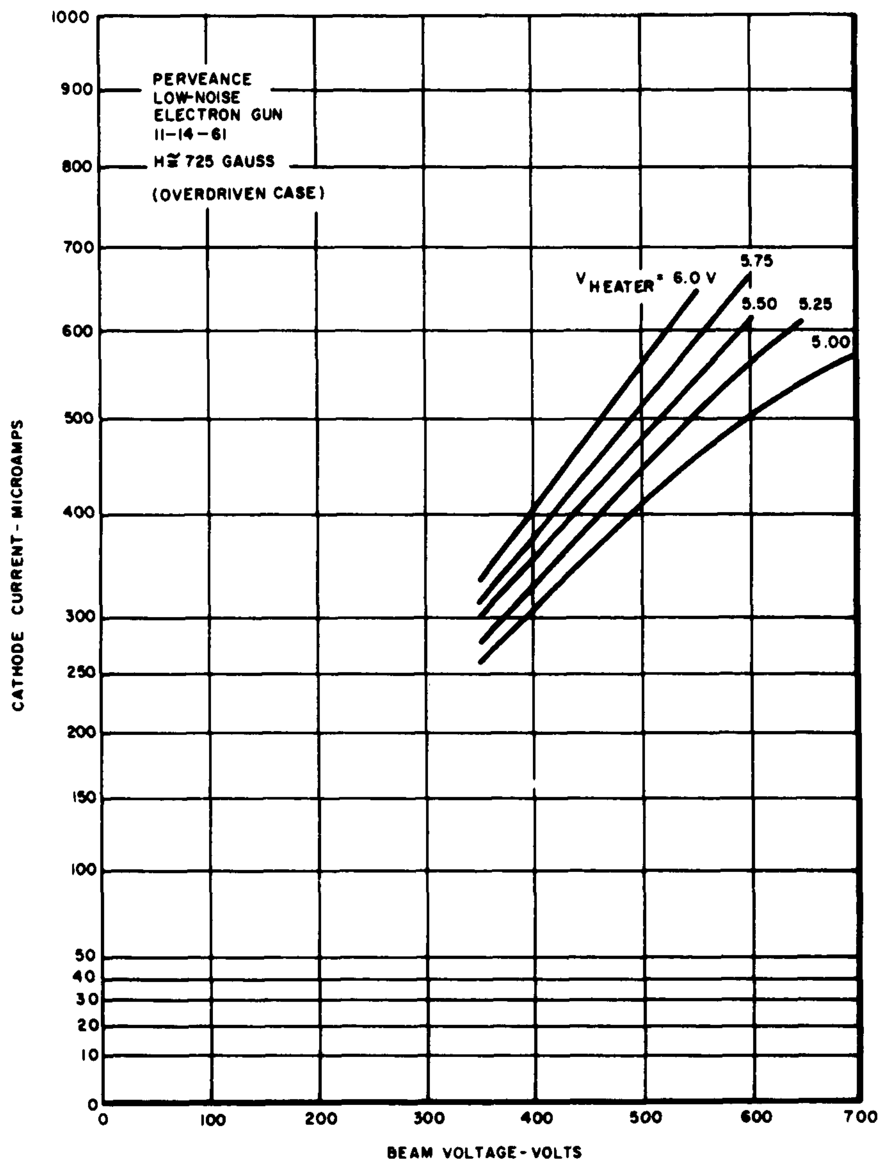

FIGURE 4. OVERDRIVEN CASE, PERVEANCE CURVE

TABLE I

LOW-NOISE ELECTRON GUN TEST PARAMETERS

Parameter	Initial	Optimum	Over driven
$V_{cathode}$(volts)	0	0	0
$V_{collector}$(volts)	900	900	600
$V_{beam\text{-}forming\ electrode}$(volts)	0	0	0
$V_{anode\ 1}$(volts)	55	60	150
$V_{anode\ 2}$(volts)	50	63	70
$V_{anode\ 3}$(volts)	270	220	110
$V_{anode\ 4}$ (volts)	900	900	600
V_{heater}(volts)	5.0	5.5	5.5
$I_{cathode}$(μa)	200	200	635
$I_{collector}$(μa)	195	197	620
*I_{magnet}(amp)	3.5	4.9	6.6
$K_o(10^{-6})$	0.0074	0.0074	0.045
% transmission	97	98.5	97.6
$J_{cathode}$(ma/cm^2)	63.3	63.3	200.0

*Aluminum wafer magnet-16 sections-rated at 110 amp/gauss.

2-2. COUPLER EVALUATION

The input, output, and local oscillator signals are to be coupled on and off the beam by means of helices wound tightly around the glass encased circuit helix. The coupling helices are wound in the opposite direction from the circuit helix. The design parameters of the coupling helices were presented in table 1 of the Second Interim Engineering Report of this contract.

The helix was wound and placed around the circuit. The entire coupler was then placed inside a brass tube. This arrangement is shown in figure 5. Cold test measurements of VSWR and transmission loss were made on all three coupling helices. Satisfactory coupling was achieved at L-band, while that at X-band proved to be unsatisfactory. The L-band coupling helix was made of 0.010-inch wire wound at 36 turns-per-inch with an inner diameter of 0.090 inch. Two couplers of this type were built. The VSWR's were measured at 1.2 and 1.08 at the center frequency of 1.5 Gc. The two couplers were placed 4.28 inches apart on a piece of circuit helix surrounded by glass, and the cold insertion loss was measured to be 7.0 db. An aquadag coating was then painted on the glass between the couplers. The resulting attenuation per length of aquadag coat was as follows:

1/4-inch aquadag coat- 8db
1/2-inch aquadag coat-12db
1-inch aquadag coat-20db
1-1/4-inch aquadag coat-27db

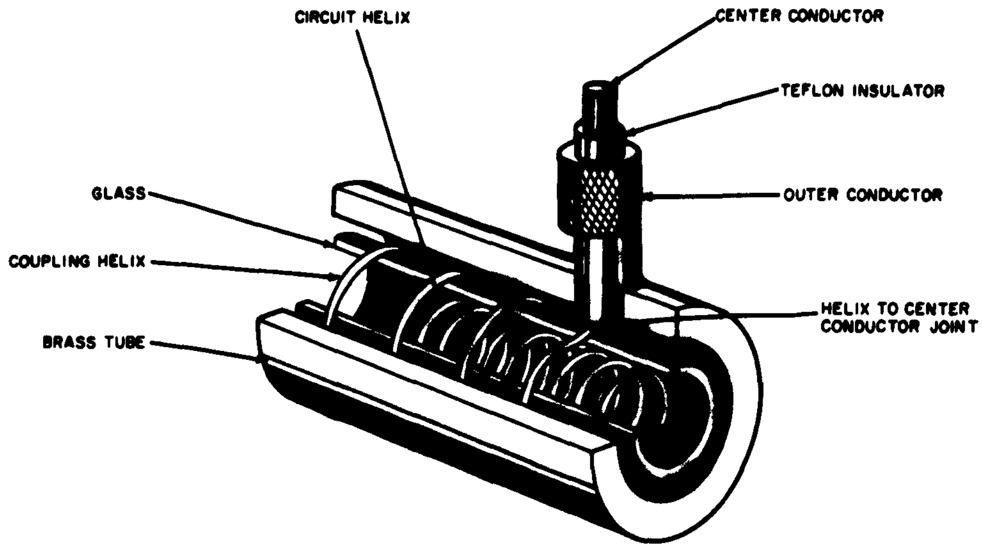

FIGURE 5. COUPLING HELIX ARRANGEMENT, 3/4-CUTAWAY VIEW

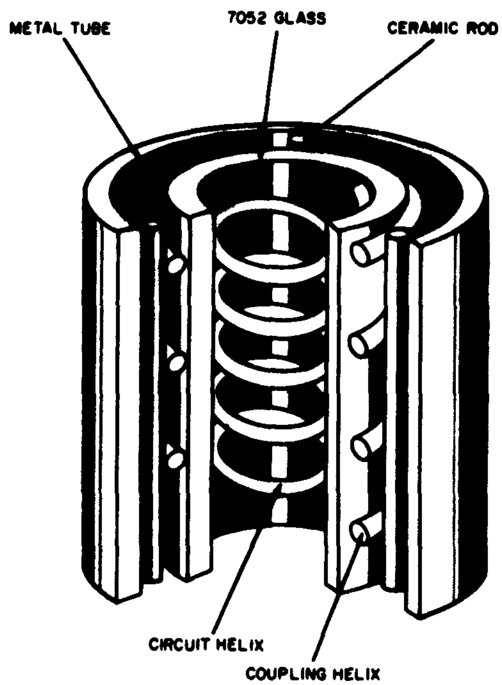

FIGURE 6. SCALED HELICES TO BE USED IN PHASE VELOCITY MEASUREMENT TESTS, 3/4-CUTAWAY VIEW

Since coupling at X-band is a necessity it was decided to abandon the tabulated design, and approach the problem from an experimental point of view. To do this it was decided to perform phase velocity measurements by bead perturbation techniques on both the internal helix and coupler helix. Because the X-band inside diameter was too small to pass a bead, a 4 times scale model was built.

The scaled helix test arrangement will have the following dimensions, and the phase velocities will be measured by the bead perturbation method. The circuit helix will be made of 0.030-inch wire with an inner diameter of 0.157 inch and will be wound at 16 turns-per-inch. It will be made of copper plated molybdenum. The coupling helix will be made of 0.128-inch copper wire wound to an inner diameter of 0.345 inch and at 5.25 turns-per-inch. The circuit helix will fit snugly inside a tube made of Corning 7052 glass with an inner diameter of 0.340 inch and a 0.060-inch wall thickness. Ceramic rods will keep the helices centered in a metal tube. This coupling arrangement is shown in figure 6. Measurements will be made at 2.375 Gc thereby achieving a frequency ratio of 4 to 1.

2-3. MAGNET

The magnet used in the low-noise electron gun tests was satisfactory for use with a tube of moderate length. Since the total length of the experimental mixer tube is approximately 24 inches long and the beam clearance is 0.009 inch, an extremely linear magnetic field

is necessary to keep the beam aligned. It is for this reason that a single core magnet was chosen for use with the tube.

The magnet chosen is 23 inches long with an outer diameter of 14 inches and an inner diameter of 6 inches (see figure 7). The magnet coil is wound with 1/8-inch copper tape at 7-1/4 turns-per-inch. For continuous operation at relatively high currents, the magnet is equipped with tubulation for liquid cooling. Tests were made to determine the field intensity along the center axis per magnet current. Figure 8 is a plot of field intensity versus length of the magnet for a constant magnet current. Both ends were covered with pole pieces made of cold rolled steel which had an outer diameter of 8 inches and inner diameter of 2 inches. The pole pieces were 1/2-inch thick. Since the field falls off at the ends of the magnet, a new pole piece design is presently being carried out to obtain maximum linearity of field at the ends of the magnet.

2-4. STATUS OF TUBE CONSTRUCTION

Construction of the experimental tube has begun and will be completed shortly. The completed tube is shown in figure 9. The low-noise electron gun is a duplicate of the one tested earlier and found to perform satisfactorily. The tubing that will encase the helices is precision Corning 7052 glass tubing. This tubing has a 0.042-inch inner diameter and a 0.015-inch wall. All

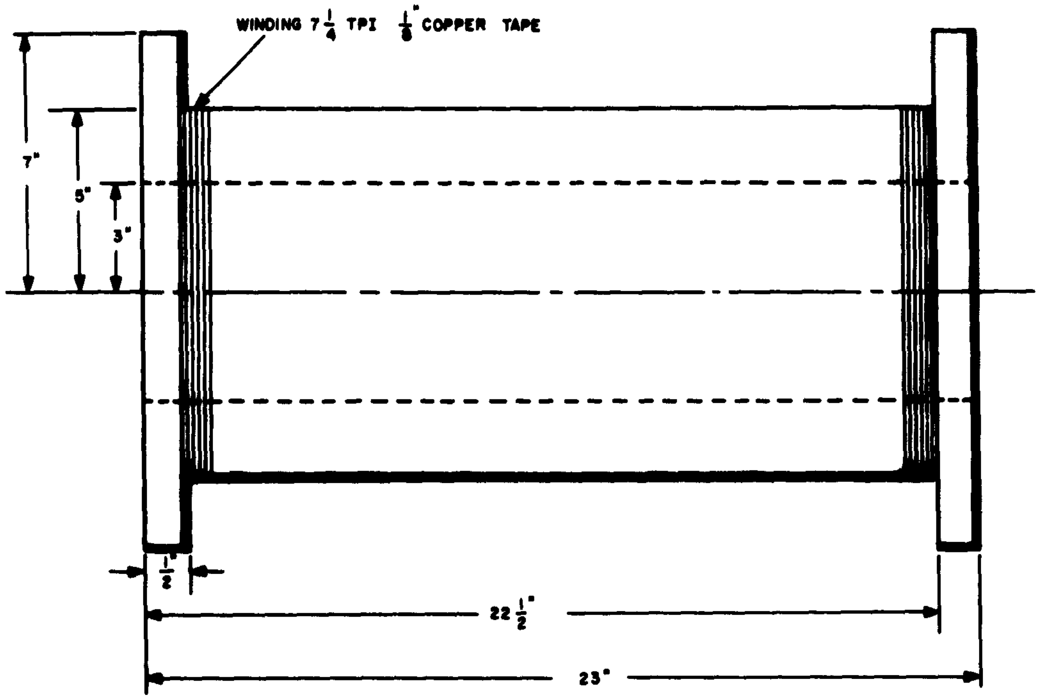

FIGURE 7. MAGNET TO BE USED WITH EXPERIMENTAL MIXER

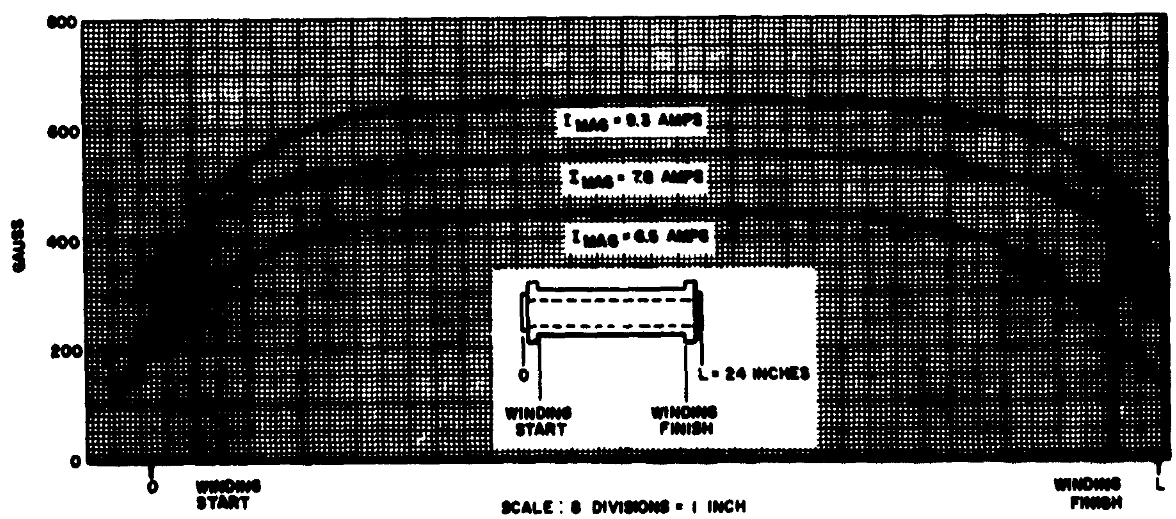

FIGURE 8. MAGNETIC FIELD VERSUS LENGTH OF MAGNET

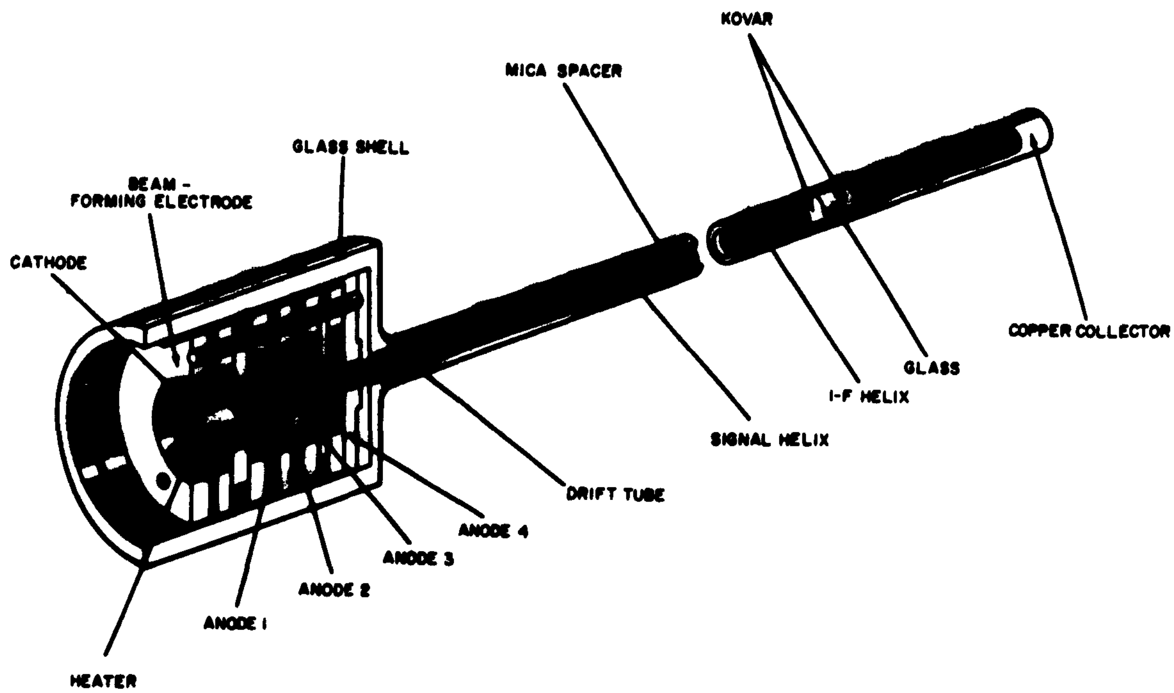

FIGURE 9. X-BAND TRAVELING-WAVE TUBE MIXER, 3/4-CUTAWAY VIEW

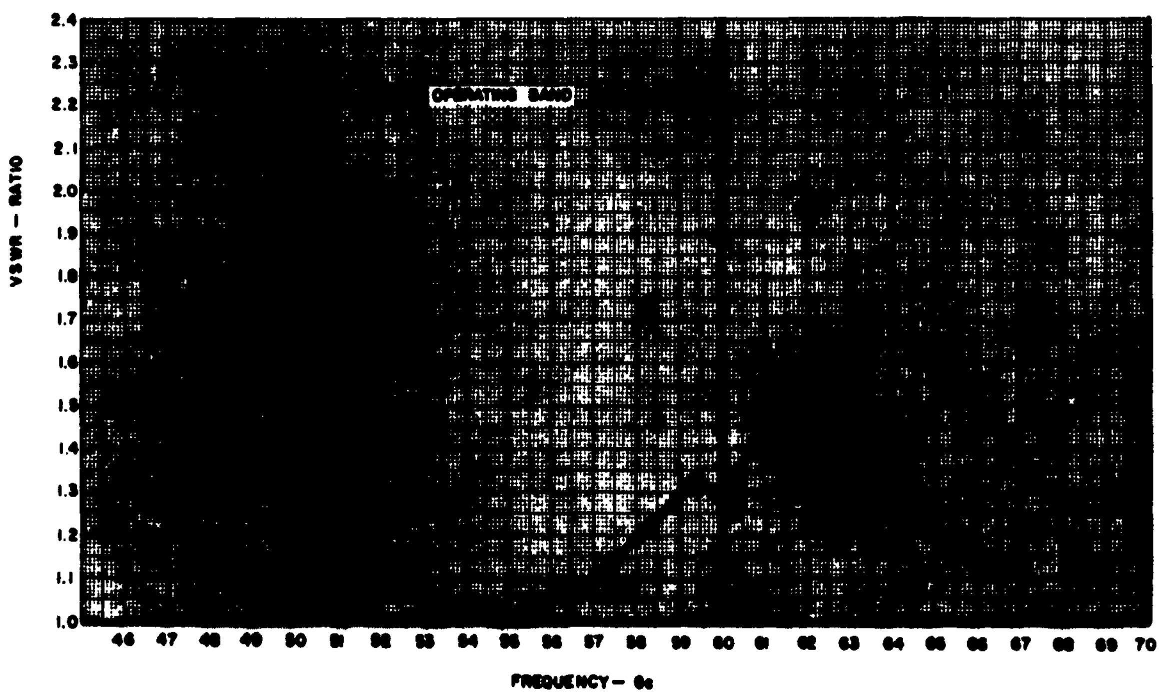

FIGURE 10. STV-197 TRANSITION MATCH (HELIX-TO-WAVEGUIDE)

glass tubing dimensions are ±0.001 inch. The glass was shrunk onto a mandrel held under tension to insure straightness. A glass-to-glass seal joins the tubing to the electron gun envelope. A glass-to-Kovar seal comprises the output end of the tube. This seal also serves as a voltage connection for the output helix.

Since the glass is straight, it was decided not to shrink it down on the helices. To prevent the L-band helix from moving around in the tube it was decided to increase its inner diameter to 0.052 inch and its outer diameter to 0.058 inch while maintaining the pitch and wire size of the original design.

The collector is made of copper and Kovar, which is sealed to a small glass bead separating the collector from the output helix. The tube is kept aligned with the magnetic field by means of an aluminum ridged V-block. The V-block will also serve as a device to adjust the camber of the tube. This will be accomplished by means of set-screws. The collector will extend beyond the end pole-piece of the magnet and will be equipped with a permanent magnet to prevent secondary electrons from re-entering the tube.

SECTION III
FULL-FREQUENCY DEVICE

Upon completion of the tests performed on the X-band traveling-wave tube mixer, a full-frequency device is to be built. This device will perform all the operations required of the X-band device but at a signal frequency of 55 Gc. Scaling the X-band device is one method of determining the dimensions of the full-frequency device. Another is to adapt a 55 Gc traveling-wave tube to perform mixing action. The latter approach is the one chosen to be followed.

A 55 Gc traveling-wave tube, the STV-197, has been designed by the Electronic Tube Division of the Sperry Gyroscope Company[7,8] . This tube will be adapted for use as the input helix and will perform the tasks of preamplification and mixing. An X-band helix will be designed to act as the i-f amplifier or second helix. The low-noise electron gun used with the X-band model will be scaled to operate with the full-frequency device.

Some of the calculated characteristics for the helix of the STV-197 are reproduced in table 2[7]. The critical watch region of the helix-to-waveguide transition is reproduced in figure 10[5].

The low-noise electron gun used with the scaled traveling-wave tube mixer must be scaled to operate with the full-frequency device since the electron gun used with the STV-197 is of the convergent type and is not of the low-noise variety. The beam diameter currently under consideration is 0.010 inch.

TABLE 2

HELIX CHARACTERISTICS OF THE STV-197

Inside Diameter	0.017 inch
Wire Size	0.003 inch
Turns-per-inch	78
Pitch	0.0128 inch
Midband γa	1.5
Interaction impedance	35 ohms
Phase velocity v/c	0.19

The same dielectric support structure used in the STV-127 will be used in the STV-197.

SECTION IV
CONCLUSIONS AND WORK DURING FORTHCOMING QUARTER

4-1. CONCLUSIONS

An analysis of the work performed has resulted in the following conclusions:

- The electron gun to be used with the experimental mixing device performed satisfactorily and will be used.
- Design of external couplers for use at X-band is very critical. Phase velocities must be precisely matched to insure the closest coupling.
- The STV-197 traveling-wave tube helix and couplers show promise of fulfilling the requirements of the full-frequency device.

4-2. WORK DURING NEXT QUARTER

Future work will involve completion of the experimental traveling-wave tube mixer and a complete evaluation of the external couplers. Testing will begin immediately upon completion of the tube and couplers. Design of the full-frequency device will begin and results of the experimental device will be applied to this design.

APPENDIX A

VELOCITY CONSIDERATIONS IN CYCLOTRON WAVE DEVICES

It has been pointed out by Gordon[9] that small variations in the axial velocities of the electrons which carry a cyclotron wave can lead to serious consequences. A somewhat simplified analysis of these problems and their consequences for cyclotron wave parametric amplifiers is discussed in the following paragraphs.

A cyclotron wave may be thought of as a helical pattern of electrons which moves in the axial direction with nearly the beam velocity u_o. The separation between crests of the pattern is the cyclotron wavelength. Any axial motion of electrons in one part of the pattern relative to another part will tend to destroy the pattern and hence the signal.

Another way to visualize the situation is to realize that the locus of electrons of a particular phase is a helix. The locus of electrons which differ in phase from the first group by π radians is another helix which is axially displaced from the first by one-half cyclotron wavelength. (See fig re A-1).

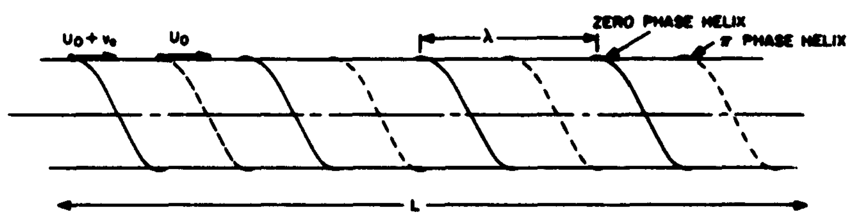

FIGURE A-1. TWO HELICES, ONE-HALF CYCLOTRON WAVELENGTH DISPLACED

If a zero phase electron has an axial velocity which is slightly higher than the velocity of the π phase electron, it will begin to overtake the π phase electron. The time it takes the electron to catch up depends on the difference in velocities and the relative distance (cyclotron wavelength). If this time is comparable to the transit time of the electrons through the circuit, the zero phase electron and the π phase electron will arrive at the same axial position at the exit plane of the circuit and will interfere destructively, completely nulling the signal.

The three major sources of variation in axial velocity about u_o, the axial beam velocity, are

- Thermal velocities
- Potential variations due to space charge
- Potential variations due to electric and magnetic lenses.

The effects of these velocity variations are discussed individually.

If the overall length of the circuit is L, then the transit time through the circuit is $\tau = L/\dot{Z}_o$ which to a first approximation is very nearly (L/u_o).

If the small differential in velocity, or ror velocity is v_e, and the cyclotron wavelength is λ, then the time it would require v_e to transport an electron a distance $\lambda/2$ is τ_e which is given by $\tau_e = \lambda/2v_e$.

If τ_e is equal to τ then during the transit through the circuit a zero phase electron will overtake a

π phase electron, and the signal will be completely destroyed. Therefore τ must be restricted to a small fraction of τ_e.

The difference in phase shift ϕ between the overtaken and overtaking electrons after they have traveled through a circuit of length L is given by

$$\phi = 2\pi \frac{v_e}{u_o} \frac{L}{\lambda}$$

and to preserve the signal, a requirement of ϕ_e is that it be a small fraction of a radian.

As the beam travels down the circuit, signal energy is coupled from the circuit to beam and noise energy from beam to circuit. The length required for complete interchange of energy is called the Kompfner dip length, and a signal coupler must be one Kompfner dip length long. The Kompfner dip length for a circularly polarized wave is given by

$$L_k = \frac{\lambda}{2} \sqrt{\frac{\omega_c}{\omega} \frac{V_o}{I_o K_t}}$$

where

ω = signal frequency

ω_c = cyclotron frequency

V_o = beam voltage

I_o = beam current

K_t = transverse Pierce impedance.

For linear polarization L_k must be multiplied by a factor of $\sqrt{2}$. If $V_e = mv_e/2e$, then this is an equivalent error potential.

In order to replace the error velocity with an error potential let

$$\frac{1}{2} mv^2 = eV; \quad \frac{dV}{V} = \frac{2v\ dv}{v^2} - 2\frac{dv}{v}$$

or

$$\frac{v_e}{u_o} = \frac{1}{2}\frac{V_e}{V_o}$$

The phase shift becomes

$$\phi = \frac{\pi}{2}\left(\frac{V_e}{V_o}\right)\sqrt{\frac{\omega_c}{\omega}\left(\frac{V_o}{I_o\ K_t}\right)} = \frac{\pi}{2}\sqrt{\left(\frac{\omega_c}{\omega}\right)\left(\frac{V_e}{I_o\ K_t}\right)\left(\frac{V_e}{V_o}\right)}$$

1. Thermal Velocities

Suppose V_e is due only to thermal velocities. The emission from a cathode is half-Maxwellian in the axial direction. At 1200°k this corresponds to about 0.2 volts. Using $\omega_c = \omega$ and $V_o = 400$v, $I_o = 5$ma, $K_T = 250\ \Omega$ yields $\phi = \pi/200$ for the thermal phase shift per coupler. This is a negligible amount.

2. Space Charge Potential Depression

The difference in potential between the beam edge and center of an immersed flow beam due to space change is given to a first approximation by

$$V_e = V_o\ (0.015)K; \quad K = \text{microperveance}$$

This causes the inside of the beam to move more slowly than the outside. The difference in phase between the inside and outside of the beam is, using $I_o = K\ V_o^{3/2} \times 10^{-6}$

$$\phi = \frac{15\pi}{2}\sqrt{\frac{\omega_c}{\omega}\left(\frac{K}{\sqrt{V_o\ K_t}}\right)}$$

Using $\omega_c = \omega$, $V_o = 400v$, $I_o = 5$ ma, $K_t = 250\,\Omega$ and $K = 0.6$ yields $\phi = \pi/10$.

Consideration is given to determine if this is a significant power loss. In order to do this, consider the fact that there is more current at the edge of the beam than in the center, and weigh the phases accordingly.

The variations in voltage across the beam are

$$V(r) = V_o\left[1 + 0.015K\left(\frac{r}{a}\right)^2\right]$$

Therefore, the variations in phase across the beam are

$$\phi = \phi_o\left(\frac{r}{a}\right)^2$$

where

$$\phi_o = \frac{15\pi}{2}\sqrt{\frac{\omega_c}{\omega}\left(\frac{K}{\sqrt{V_o\ K_t}}\right)}$$

The current between r and r + dr is $I = 2\pi r\ \rho dr$

where

ρ = current density

The relative signal loss is then

$$\psi = \frac{\int_0^a I \cos \phi dr}{\int_0^a I\, dr}$$

$$\psi = \frac{\int_0^a 2\bar{a}\ \rho r \cos \left[\phi_o \frac{r^2}{a^2}\right] dr}{\int_0^a 2\pi\ \rho r\ dr}$$

$$\psi = - \frac{\sin \phi_o}{\phi_o}$$

and the power variations are

$$\psi^2 = \frac{\sin^2 \phi_o}{\phi_o^2}$$

For $\phi_o = \pi/10$ the power is down by three percent at the end of the coupler.

3. Lens Effects

At the present time, no good basis has been established for estimating the order of magnitude of the velocity variations due to electrostatic and magnetic lens effects introduced in the gun and focusing systems.

Gordon(9) estimates these effects to be ten times the space charge spread. If this figure is used it gives a phase spread of $\phi_o = \pi$ which attenuates the signal.

APPENDIX B
REFERENCES

1. R. Adler, "The Quadrupole Amplifier", Proc. I.R.E., Vol. 47, pp. 1713-1723 October 1959

2. A. Askin, "A Low-Noise Microwave Quadrupole Amplifier", Proc. I.R.E., Vol. 49 p. 1016, June 1961

3. G.W. Hrbek, "A Non-Degenerate Electron Beam Parametric Amplifier", paper presented at the Electron Devices Meeting, Washington, D.C. 1961

4. M. Caulton and G.E. St. John, "S-Band Traveling Wave Tube with Noise Figure Below 4 DB.", Proc. I.R.E., Vol. 46, pp. 911-912, May 1958

5. M.R. Currie and D.C. Forster, "Low Noise Tunable Preamplifiers for Microwave Receivers", Proc. I.R.E., Vol. 46, pp. 570-579, March 1958

6. A. Zacharias and L. Smullin, Report No. 358, Noise Measurements on Electron Beams at 3000 Mc, MIT Research Laboratory for Electronics, November 1959

APPENDIX B
REFERENCES

7. Applied Research on a High-Power V-Band Amplifier - Interim Engineering Report No. 1, furnished by the Sperry Gyroscope Company to the Aeronautical Systems Division, Wright Air Development Division, under Contract No. AF33(616)-8292, August 1961.

8. Applied Research on a High-Power V-Band Amplifier - Interim Engineering Report No. 2, furnished by the Sperry Gyroscope Company to the Aeronautical Systems Division, Wright Air Development Division, under Contract No. AF33(616)-8292, November 1961.

9. E.I. Gordon - Private Communication.